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Two different ways in evaluating the uncertainty of S-parameter measurements

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***Abstract* – The expression of uncertainty of scattering parameter measurements in vector network analysis is an active research subject, since no full consensus about proper algorithms for such expression has been reached so far. Recently, two software packages have been acquired at INRIM, which allow to perform this task in a metrological framework. In this paper we compare the result of analysis performed by two packages, `VNA Tools II` and `Multiport Measurement Software version 4 (MMS4)`. Both packages claim to perform uncertainty analyses fully compliant to the *Guide of expression of uncertainty in measurement*, but following completely different approaches. We organized a comparison by performing, with both packages, analyses of the very same datasets. These have been generated by real measurements on passive standards with a commercial vector network analyzer. Results of the comparison give consistency of the uncertainty analyses performed by the software packages, which can be therefore considered equivalent and mutually validated.**

I. INTRODUCTION

Any measurement is as good as its uncertainty. The uncertainty expression in vector network analysis, and in particular in the measurement of scattering matrix elements of multiport networks, is the subject of present active developments in microwave field [1]. Official guidelines in force [2] are based on assumptions that have been demonstrated failures [3] and therefore different mathematical approaches have been proposed [4–6]. Further, because of the large dataset size involved in vector network analyzer (VNA) measurements and the need to deal with complex numbers, the analysis has to be performed through dedicated software packages.

Recently, two specific software packages have been released, `VNA Tools II`[1] and `MMS4`[2]. The packages take full control of the whole measurement process, including the VNA calibration with passive standards, and provide as result the scattering parameter estimates together with the associated standard uncertainties and covariances. Both packages claim an uncertainty expression compliant with the *"Guide to the expression of the uncertainty in measurements - (GUM)"* [7], but the packages have different management of uncertainty databases, and rely on different mathematical foundations. Hence, a comparison of the software packages results on the very same measurement is meaningful and of particular interest.

[1]`VNA Tools II` [5] is developed by Bundesamt für Metrologie (METAS).

[2]`Multiport Measurement Software version 4 (MMS4)` is a commercial software developed by High Frequency Engineering (HFE), Switzerland.

II. SOFTWARE PACKAGES

`VNA Tools II` and `MMS4` employ two different measurement models, briefly referenced here.

A. *VNA Tools II*

The measurement model employed by `VNA Tools II` is extensively described in [5, Eq. 1] and [8].

The uncertainty sources considered by the package are [5]:

1. Noise floor and trace noise of the VNA
2. Linearity of the VNA
3. Drift of switch and error terms of the calibration
4. Cable stability
5. Connector repeatability
6. Definition of the calibration standards.

A linear propagation of the uncertainty through the model is employed (see [5, eq. 2, 3 and 5]), and implemented with METAS UncLib [9], a general purpose library that can manage multivariate analyses [7] and is based on the `GUM Tree` algorithm [10–12].

B. *MMS4*

The measurement model and the uncertainty evaluation analysis implemented in `MMS4` is thoroughly described in [6].

The uncertainty sources considered by `MMS4` are:

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1. Measurement noise

2. Connector (and cable) repeatability

3. Definition of the calibration standards.

The propagation of the uncertainty follows a fully analytical approach evaluated *a priori* by the developers [6, Eq. 5]; the resulting equations are directly implemented in the package.

The A and B models adopt a different classification in number and type of the uncertainty sources, but this is not significant in the frame of out comparison. Because it is not possible to know the details of the code lines of the two softwares, it is not possible to say on the fullness of them a priori. Only the bare comparison of the final results allows to determine if something important has been neglected in one of the two packages.

III. THE COMPARISON PROCESS

In order to achieve a meaningful comparison of the outputs of the two packages, both have been executed under the same calibration process, with the same data for the calibration standards and by analysing the same S-parameters, each one coming from real measurements. In this manner, the compatibility between package outputs can be entirely ascribed to the algorithms implemented for de-embedding the measured S-parameters, and for expressing their uncertainty.

A. Calibration algorithm

Both software packages allow the selection of a calibration process from predefined lists; we have chosen the QSOLT (Quick Short Open Load Thru) one [13] since it is implemented in both packages. QSOLT requires the measurement of three one-port standards (Short, Open, and Load) at one VNA port, plus one two-port standard (Thru) between the two ports of the instrument.

B. Package databases

The databases of `VNA Tools II` and `MMS4` which include information about the uncertainty sources are quite different, because the uncertainty sources considered are differently defined in the two models adopted (see Sec. ii.).

The uncertainty contributions caused by VNA nonlinearity and drifts are taken into account by `VNA Tools II` but not by `MMS4`. For this reason, we eliminated this contribution from `VNA Tools II` database.

Uncertainty contributions related to cables and connectors are considered by both software packages, though in a very different way. `VNA Tools II` treats the uncertainty due to cables and connectors separately, as Type B contributions related to cable stability and connector repeatability; instead, `MMS4` considers the repeatability as due to the influence of both cable and connectors together, and reports a type A estimation of the corresponding uncertainty contributions from repeated measurements. Because of the intrinsic differences in the definition, no consistent way to treat such error source has been identified. Therefore these have been excluded from the databases. A similar problem occurs in the definition of measurement noise; this uncertainty contribution has also been purged.

The definition of the calibration standards, and the corresponding uncertainty contributions, are treated in a consistent way by both packages – even though coded in different ways into the two databases. We have started with the `VNA Tools II` standard definitions and computed, for each standard, the corresponding scattering parameter matrix (and associated uncertainties). Such matrices have been employed as input data of the `MMS4` package.

C. Raw measurements

It must be explicitly remembered that we performed the comparison on actual measurements, instead of using simulated data.

`VNA Tools II` / `MMS4` typical measurement sequence involves the connection of each calibration standard and of each device under test (DUT) to the VNA ports. For each DUT, a scattering parameter measurement is performed, and a raw data file is saved. The software packages perform the model calculation and uncertainty evaluation, while the error correction procedures embedded in the instrument firmware are not employed.

For technical reason and convenience, since it is easier to convert raw data from `MMS4` to `VNA Tools II` than doing the reverse, all measurements have been collected with `MMS4`. The data recording structures of the two packages is completely different, therefore dedicated software routines for `MMS4` to `VNA Tools II` conversion have been developed.

Raw measurements have been obtained from a VNA Agilent E8364C equipped with semirigid cable HP 85134D ($2.4\,\mathrm{mm}$ - $3.5\,\mathrm{mm}$). All DUTs are two port devices that present one male port and one female port; for each DUT, all four S-parameters have been measured. VNA has been set to present male connector at port 1, and female at port 2.

The standards and the DUTs used in this comparison are presented in Tab. 1, where their significant properties are described.

The characteristic values and uncertainties of the standards are predefined in the `VNA Tools II` database. The values correspond to the "Standard Definitions" in [14, Sec. A.2]; the uncertainties are expressed as "Electrical Specifications" [14, Tab. 2-3].

The DUTs chosen are a $50\,\Omega$ airline, a $25\,\Omega$ airline, and a series of attenuators ranging from $6\,\mathrm{dB}$ to $40\,\mathrm{dB}$. Con-

Table 1. Standards and DUTs employed during the comparison.

type	device	model	connector [mm]	ref
Std.	open M	HP 85052-60008	3.5	
	open F	HP 85052-60009	3.5	
	short M	HP 85052-60006	3.5	
	short F	HP 85052-60007	3.5	
	load M	HP 902C	3.5	
	load F	HP 902D	3.5	
	thru	Ideal thru	3.5	
DUTs	6 dB Att.	Weinschel 54-10	2.92	
	10 dB Att.	Weinschel 54A-6	2.92	
	20 dB Att.	HP 85053-60001	3.5	Re[S_{21}]: Fig. 1 Im[S_{21}]: Fig. 2
	40 dB Att.	HP 85053-60002	3.5	
	50 Ω Line	HP 85053-60005	3.5	
	25 Ω Line	HP 85053-60006	3.5	Re[S_{11}]: Fig. 3 Im[S_{11}]: Fig. 4

nector types are $3.5\,\mathrm{mm}$ and $2.92\,\mathrm{mm}$, which are mechanically compatible. Measurements have been performed at the nominal power level of $-17\,\mathrm{dB}$, that is the default level set by the instrument; the frequency range is between $50\,\mathrm{MHz}$ and $26.5\,\mathrm{GHz}$.

IV. RESULTS

The availability of measurements on several DUTs over a wide frequency range allow the comparison of software package outcomes over a large dataset. For each element of the dataset, the measurement estimate (the output of the measurement model) is dependent on the calibration values provided for the standards, but in a different way; hence, the measurement uncertainty estimated by the packages will be dependent on the input uncertainties with different sensitivity coefficients, thus allowing a more extensive comparison.

Standard and DUT measurements have been processed by both software packages, which provide estimates of S-parameters and associated uncertainty,standard or expanded (2σ coverage factor). An example of comparison of the results obtained is shown in Figs. 1–4; similar outcomes and discussion apply to all other analyses performed.

Figures 1–4 are splitted in three parts, top, middle and bottom. Top part of each figure gives a plot of the real or imaginary part of the scattering parameter versus frequency (for example, $\mathrm{Re}[S_{11}]$), together with the corresponding uncertainty bars,[3] for example $U(\mathrm{Re}[S_{11}])$; the lines are a guide to the eye. Middle part of each figure focuses on the differences between `VNA Tools II` (subscript v) and `MMS4` (subscript m) outcomes in the estimates (for example, $\mathrm{Re}[S_{11}^{(\mathrm{v})}] - \mathrm{Re}[S_{11}^{(\mathrm{m})}]$). Finally, bottom part of each figure focuses on the differences between `VNA Tools II` (subscript v) and `MMS4` (subscript m) outcomes in the associated standard uncertainties (for example, $u(\mathrm{Re}[S_{11}^{(\mathrm{v})}]) - u(\mathrm{Re}[S_{11}^{(\mathrm{m})}])$). Again, the lines are just a guide to the eye.

[3]Differences between software outputs are too small to be visible in this representation; therefore, only the `VNA Tools II` results are plotted.

Table 2. Uncertainty budgets for $20\,\mathrm{dB}$ *attenuator and* $25\,\Omega$ *airline.*

		13 GHz		20 GHz	
		Real	Imaginary	Real	Imaginary
20 dB Att. S_{21}	Load	84%	84%	7%	7%
	Open	9%	9%	53%	53%
	Short	7%	7%	40%	40%
	Total	100%	100%	100%	100%
25 Ω Line S_{11}	Load	87%	87%	10%	10%
	Open	6%	6%	82%	82%
	Short	7%	7%	8%	8%
	Total	100%	100%	100%	100%

Figures 1 and 2 refer to S_{21} measurements on $20\,\mathrm{dB}$ attenuator, real (Fig. 1) and imaginary (Fig. 2) parts.

Figures 3 and 4 refer to S_{11} measurements on $25\,\Omega$ airline, real (Fig. 3) and imaginary (Fig. 4) parts.

V. DISCUSSION

As said in Sec. iv., the purpose of performing the comparison on different devices and in a wide frequency range is to test the algorithms on measurements of quantities having different values, and which uncertainties are dependent on the input uncertainties with widely varying sensitivity coefficients – hence, with varying weights on the associated uncertainty budgets. Tab. 2 gives four examples of such budgets[4], obtained for two specific frequency points (13 GHz and 20 GHz) on the same data displayed in Figs. 1 – 4. The differences in the weights associated with the input uncertainties related to the calibration standard definitions can be easily appreciated.

As already mentioned, middle and bottom parts of each figure focuses on the differences between `VNA Tools II` (subscript v) and `MMS4` (subscript m) outputs. Both the differences in the estimates (e.g $\mathrm{Re}[S_{11}^{(\mathrm{v})}] - \mathrm{Re}[S_{11}^{(\mathrm{m})}]$) and in the associated uncertainties (e.g. $u(\mathrm{Re}[S_{11}^{(\mathrm{v})}]) - u(\mathrm{Re}[S_{11}^{(\mathrm{m})}])$) are displayed.

These difference have been evaluated to be less than 10^{-5} (very often less than some parts in 10^{-6}) in magnitude for all the results obtained, both for the S-parameters and for their uncertainties. Such a small threshold has been

[4]For each budget, the real and imaginary parts of the same quantity have similar weights; this is caused by the way the uncertainty of a standard in `VNA Tools II` is defined, since a single contribution is provided and equally assigned to both real and imaginary components of a parameter.

traced back to the numerical rounding when reading the data files.

For what concerns the uncertainty sources neglected in the comparison ad mentioned in Sec. B., it has been observed that their influence is negligible or can be reduced by performing the measurements with proper care (e.g., by performing measurements immediately after calibration, by minimizing cable movements and by employing a torque wrench for the connector engagement).

VI. CONCLUSIONS

The paper describes a comparison between two different software packages, `VNA Tools II` and `MMS4`, which have been developed to perform data acquisition, analysis and uncertainty evaluation of measurements acquired with a vector network analyzer. The same set of raw data have been fed to both packages, together with identical descriptions of the standards employed for the VNA calibration. The raw data, collected in a wide frequency range and on several devices, tested the software packages on a wide range of frequencies, scattering parameter values, and weights of contributions to the uncertainty budgets of the measurands.

A substantial agreement between the outcomes of the two software packages is achieved,, both in the scattering parameter estimates and corresponding standard uncertainties, is achieved. Therefore, the result of the comparison can be interpreted as a mutual validation of the software packages and in particular of the algorithms there implemented, at least for what concerns the error propagation related to the calibration standards.

Since the very expression of the uncertainty contribution relateds to to noise, drifts, connector and cable instabilities is different in the two packages, a validation through comparison cannot be performed. Only a consensus at the scientific level about how to express such uncertainty contributions will allow an extension of the direct comparison method followed in this paper.

VII. ACKNOWLEDGMENT

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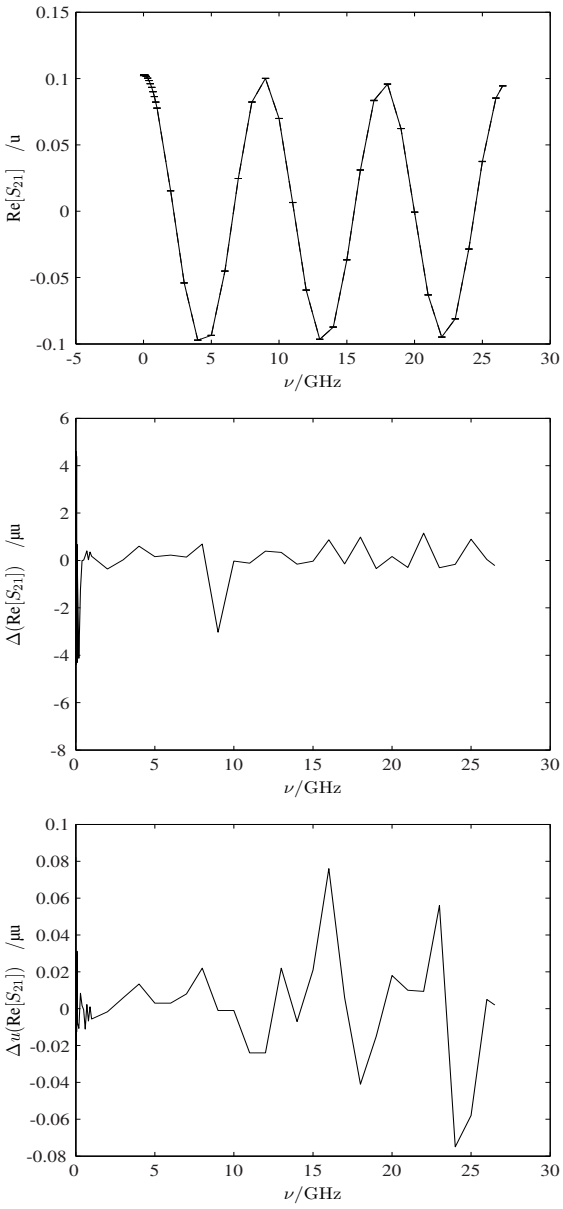

Fig. 1. (top) Real part of the transmission parameter S_{21} for 20 dB *attenuator. (middle) Difference between* `VNA Tools II` *and* `MMS4` *results for Re[S_{21}] and (bottom) Difference between* `VNA Tools II` *and* `MMS4` *results for u(Re[S_{21}]) for the same attenuator; vertical axis ticks are in microunits,* µu *(10^{-6}); Δ represents a difference.*

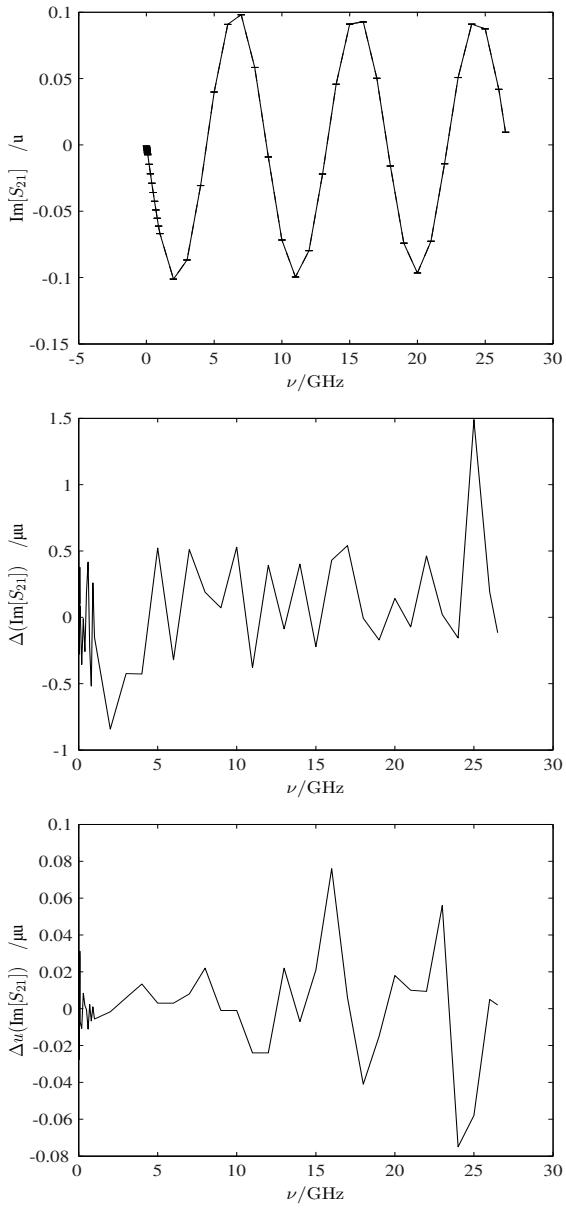

Fig. 2. (top) Imaginary part of the transmission parameter S_{21} for 20 dB *attenuator. (middle) Difference between* `VNA Tools II` *and* `MMS4` *results for Im[S_{21}] and (bottom) Difference between* `VNA Tools II` *and* `MMS4` *results for u(Im[S_{21}]) for the same attenuator.*

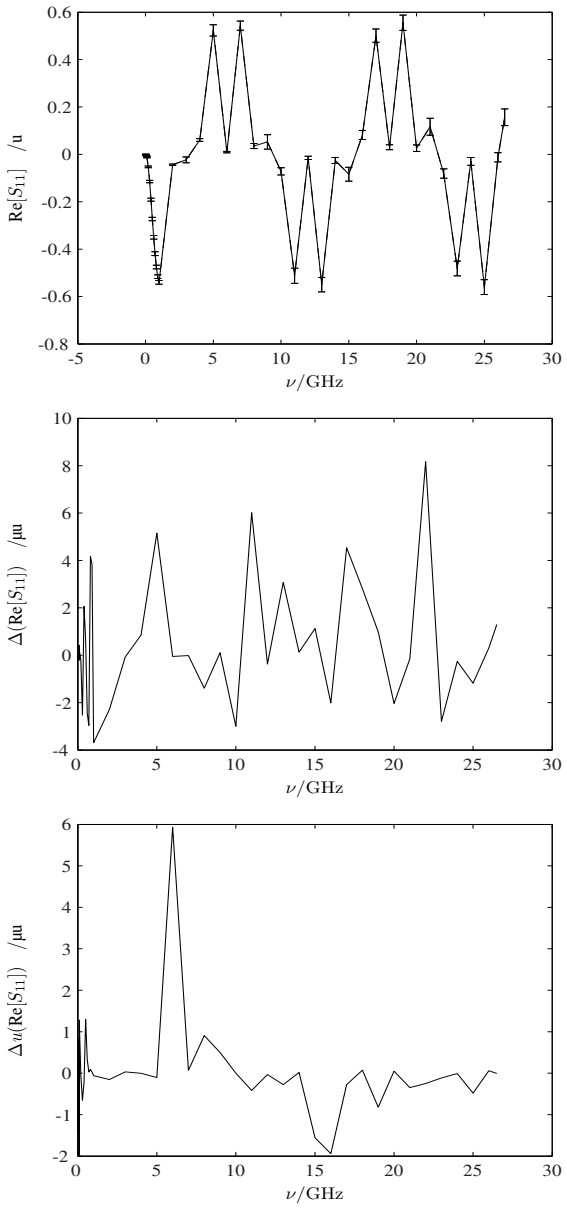

Fig. 3. (top) Real part of the reflection parameter S_{11} for $25\,\Omega$ airline. (middle) Difference between `VNA Tools II` and `MMS4` results for Re[S_{11}] and (bottom) Difference between `VNA Tools II` and `MMS4` results for u(Re[S_{21}]) for the same airline.

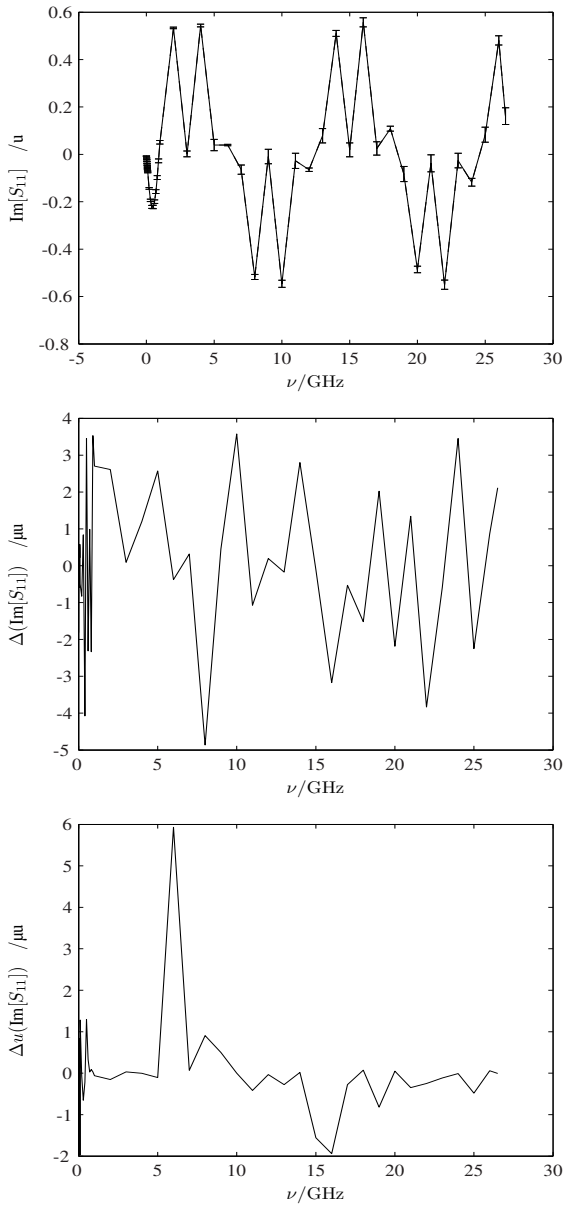

Fig. 4. (top) Imaginary part of the reflection parameter S_{11} for $25\,\Omega$ airline. (middle) Difference between `VNA Tools II` and `MMS4` results for Im[S_{11}] and (bottom) Difference between `VNA Tools II` and `MMS4` results for u(Im[S_{11}]) for the same airline.

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